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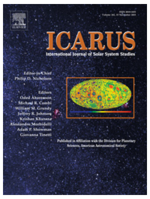

Re-analysis of previous laboratory phase curves: 2. Connections between opposition effect morphology and spectral features of stony meteorites

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ABSTRACT

We investigate connections between the opposition phase curves and the spectra from ultraviolet to near infrared wavelengths of stony meteorites. We use two datasets: the reflectance dataset of Capaccioni et al. ([1990] Icarus, 83, 325), which consists of optical phase curves (from 2° to 45°) of 17 stony meteorites (three carbonaceous chondrites, 11 ordinary chondrites, and three achondrites), and the spectral dataset from the RELAB database consisting of near-ultraviolet to near-infrared spectra of the same meteorites. We re-analyzed the first dataset and fit it with two morphological models to derive the amplitude A, the angular width HWHM of the surge and the slope S of the linear part. Our re-analysis confirms that stony meteorites have a non-monotonic behavior of the surge amplitude with albedo, which is also observed in planetary surfaces (Déau et al. [2013] Icarus, 226, 1465), laboratory samples (Nelson et al. [2004] Proc. Lunar Sci. Conf., 35, p. 1089) and asteroids (Belskaya and Shevchenko [2000] Icarus, 147, 94). We find a very strong correlation between the opposition effect morphological parameters and the slope of the spectra between 0.75 μm and 0.95 μm. In particular, we found that meteorites with a positive amplitude-albedo correlation have a positive spectral slope between 0.75 μm and 0.95 μm, while meteorites with a negative amplitude-albedo correlation have a negative spectral slope between 0.75 μm and 0.95 μm. We have ruled out the role of the meteorite samples' macro-properties (grain size, porosity and macroscopic roughness) in the correlations found because these properties were constant during the preparation of the samples. If this hypothesis is correct, this implies that other properties like the composition or the micro-properties (grain inclusions, grain shape or microscopic roughness) could have a preponderant role in the non-monotonic behavior of the surge morphology with albedo at small and moderate phase angles. Further accurate characterization of carbonaceous chondrites samples are necessary to draw conclusions about the role of the micro-properties.

1. Introduction

The phase curve (which represents the surface reflectivity as a function of the phase angle) of a surface depends on its intrinsic physicochemical properties: the internal structure of the grains, the grain size distribution, the composition, the porosity, and the surface texture (Cord et al., 2003; Hapke, 1993; Mishchenko et al., 2002; Shepard and Helfenstein, 2007; Shkuratov et al., 2011, 2002, 2005a). The crucial importance of planetary phase curves lies in the possibility to derive these properties from the phase curve data and an inversion method (e.g. a fit with a radiative transfer model). Phase curves (and particularly "normal reflectance") also have practical applications as they are crucial for dimensioning the design of laser transmitters and receivers (Gardner, 1982; Thomas et al., 2007).

The most remarkable peculiarity of the phase curves is that they often exhibit an opposition effect (see Gehrels, 1956), which is characterized by:

(1) a surge, i.e. a nonlinear increase in the intensity of scattered light, occurring when the phase angle decreases below 5° (Müller, 1885; Seeliger, 1884), and
(2) a linear increase in the intensity of scattered light for phase angles up to 40° (Belskaya and Shevchenko, 2000).

These two features can be translated in terms of morphology with the amplitude, the angular width of the surge and the slope of the linear part, see Part 1 of our paper series (Déau et al., 2013).

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The opposition effect morphology can be predicted by opposition effect mechanisms. The first one, shadow hiding, consists of the progressive disappearance of mutual shadows of irregularities on the surface. Shadow hiding was historically introduced by Seeliger (1887), Bobrov (1961), Hapke (1963), and Irvine (1966), and consisted of studying the shadows of a simple homogeneous surface. Recent works, e.g. Shkuratov and Helfenstein (2001), have studied the influence of hierarchical structures on the shadow effect. The shadow hiding effect in optically inhomogeneous media has also been studied, (Stankevich and Shkuratov, 2004).

The second mechanism, coherent backscattering, is caused by waves propagating in a reversed path through a medium that interfere constructively in the backward direction (Kuga and Ishimaru, 1984; Tsang and Ishimaru, 1985; Wolf and Maret, 1985). An analysis of the different mechanisms influencing the opposition phase curves is presented in Shkuratov et al. (2012).

Another way to consider the opposition effect is with Mie theory and Maxwell equations, which are also able to produce an opposition surge (Egan and Foreman, 1971; Mishchenko et al., 2006). However, such theories require small grain sizes and high albedo materials. As a result, these theories cannot completely explain completely the opposition effect of dark objects (Muinonen, 1994). For dark particulate surfaces, single-grain scattering could significantly contribute to the phase curves, when the shape of grain is irregular, e.g. (Petrov et al., 2012; Shkuratov et al., 2007; Zubko et al., 2015), and even when the grains are very large compared to the wavelength, e.g. (Shkuratov and Grynko, 2005).

It is thus likely that the amplitude and the angular width of the surge are mainly due to the opposition effect mechanisms (Hapke, 1986; Hapke, 2002; Shkuratov et al., 1999). By contrast, the role of the single scattering phase function and multiple scattering cannot be neglected in the slope of the linear part (Okada et al., 2006; Stankevich and Shkuratov, 2002; Stankevich et al., 1999).

One of the most commonly used techniques in photometry is the inversion method, which consists of deriving physicochemical properties of a surface that has only been observed remotely. The opposition effect, by itself, could allow the derivation of the surface's physicochemical properties, when combined with an inversion method using accurate opposition effect models. However, this method is not totally validated yet because there are debates about the coherent backscattering formalism (Hapke and Nelson, 2010; Tishkovets and Mishchenko, 2010). These debates are clearly due to the fact that too few laboratory samples have been used to constrain and improve the models, see (Déau et al., 2013; Hapke, 2008; Shepard and Helfenstein, 2007; Tishkovets and Mishchenko, 2010).

So far, the works of Kaasalainen (2003) (and more recently Déau et al. 2013) have helped the field converge toward a unique vision on how the opposition morphology varies with the sample properties, see also (Cord et al., 2003; Shkuratov et al., 2007). The further step – that has been started recently – is to compare the opposition morphology from the models to those from the laboratory samples, see (Hapke, 2008; Nelson et al., 1998). We summarize in the following paragraphs the main findings:

- The slope of the shadow hiding mainly varies with the mechanical properties of the medium, as demonstrated by laboratory photometry experiments (Cord et al., 2005; Hapke and Sato, 2015; Shkuratov et al., 2012, 2005b). However, the shadow hiding effect from the surface topography may also be influenced at phase angles more than several tens of degrees (Shkuratov et al., 2012, 2005b).
- The amplitude and width of the shadow hiding mainly vary with the mechanical properties of the medium (porosity, see Hapke, 1986; Hapke, 2008; Stankevich et al., 1999). Since shadow hiding's nature is due to the grain layout in the medium, this effect is mainly wavelength-independent (Muinonen, 1994). This has been demonstrated by the laboratory experiments of Shkuratov et al. (1999), where a "pure shadow hiding" surface has a flat color ratio, while a "shadow free" surface exhibits a strong opposition surge as well as large variations of color ratio with phase angle.
- For coherent backscattering, the amplitude and width of this effect depend, to first order, on the chemical composition (Mishchenko, 1992; Mishchenko and Dlugach, 1992), and on the grain size, porosity and roughness at higher orders. As a result, it appears that shadow hiding does not create spectral features (Shkuratov et al., 1999), while coherent backscattering does, see also (Kolokolova et al., 2011).

Using a set of laboratory samples where the chemical composition is changed while the mechanical properties (grain size, porosity, and roughness) remain constant could represent a unique opportunity to test the behavior of the two physical processes believed to be involved in the opposition effect. So far, in spite of multiple laboratory studies on the opposition effect (Jost et al., 2016; Kaasalainen, 2003; Shepard and Helfenstein, 2007; Shkuratov et al., 1999, 2002, 2007), no experiment has been able to describe in detail the degree of coupling between coherent backscattering and shadow hiding in the resulting formation of the opposition surge. The goal of this paper is to address this problem by searching for connections between the opposition effect morphology and spectral features of laboratory samples.

For the laboratory samples, we have chosen meteorites, because they are among the few extra-terrestrial material that can potentially be observable by a large part of the laboratory community. Moreover, compared to other laboratory powders, stony meteorites offer a complexity similar to asteroids in terms of physicochemical properties (Consolmagno et al., 1998; Feierberg, 1981; Gaffey et al., 1993; Lazzarin et al., 1997) because of the likely common-parent origin (Bradley and Brownlee, 1991; Britt and Consolmagno, 2000; Flynn et al., 1999; Greenberg and Chapman, 1984; Hiroi et al., 2001; Taylor et al., 1987) in spite of a different chemical evolution (Vernazza et al., 2008, 2009, and references therein).

While stony meteorite samples are easily accessible, their opposition effect has not been analyzed in detail (Beck et al., 2012; Capaccioni et al., 1990; Kaasalainen et al., 2002; Kamei and Nakamura, 2002; Sakai et al., 2003). The dataset used here consists of optical phase curves observed by Capaccioni et al. (1990, hereafter C1990). C1990 provided a limited effort in the use of modeling to interpret their results. Considering that no other measurements of such wide range of meteorites samples with high phase angle resolution near zero phase are presently available, the intention of our paper is to improve the work of C1990, to give additional insights on the connections between the opposition effect morphology and spectral features, and therefore, possibly draw conclusions on the role of coherent backscattering and shadow hiding in the opposition effect.

In Section 2, we present our methodology, first by introducing the data used in this work (Section 2.1) i.e. opposition phase curves and optical to near-infrared spectra of the stony meteorites. Section 2.2 presents the methodology as well as the models (morphological and physical) used to fit the phase curves and spectra data. In Section 3, we present the results of our modeling for the meteorites samples. In Section 4, we discuss these comparisons in the framework of the shadow hiding and coherent backscattering models. A summary of the results is given in Section 5.